Metrology for the *StarLight* Stellar Interferometry Mission

Serge Dubovitsky, Oliver Lay and Alex Abramovici
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr. m/s 301-451, Pasadena, CA, 91109, USA
e-mail: *serge.dubovitsky@jpl.nasa.gov*

Abstract – We describe the Metrology System for NASA's *StarLight* mission, a space-based separated-spacecraft stellar interferometer. It consists of dual-target linear metrology, based on a heterodyne interferometer with carrier phase modulation, and angular metrology designed to sense the pointing of the laser beam. The dual-target operation enables one metrology beam to sense displacement of two targets independently.

1 THE *StarLight* MISSION

NASA's StarLight mission, scheduled for launch in 2006, will be the first formation-flying optical interferometer in space. The goal of the 6-month mission is to demonstrate the technology that will be needed for future astrophysics missions, such as the Terrestrial Planet Finder. The two spacecraft configuration (Fig. 1a) has a projected baseline that varies between 30 and 125 m as the separation is increased from 40 to 600 m. The collector spacecraft relays the incoming starlight to the combiner spacecraft, where it is combined with light that enters the combiner directly. To obtain an interference pattern, the two paths from the star to the beam combiner must be equalized to a fraction of a micron. A 14 m fixed delay line on the right side of the optical path (Fig. 1b) compensates for the gross geometrical offset in path length. A variable delay line on the left side of the Combiner optics is used to actively compensate for the small motions of the spacecraft. Further details can be found in reference [1]. The metrology system serves four primary purposes: (1) Measure the rate of change of the separation between the spacecraft, i.e. the range rate. A separate RF sensor is used to measure the absolute range. (2) Measure the position of the variable delay line. (3) Measure any high frequency jitter in the optical path lengths through the system. (4) Provide a sensor to ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics. The Linear Metrology system addresses (1), (2), and (3); the Angular Metrology system addresses (4).

2 LINEAR METROLOGY

2.1 Dual Target Metrology

The StarLight linear metrology system operates at 1320 nm, with independent gauges to monitor the left and right optical paths through the

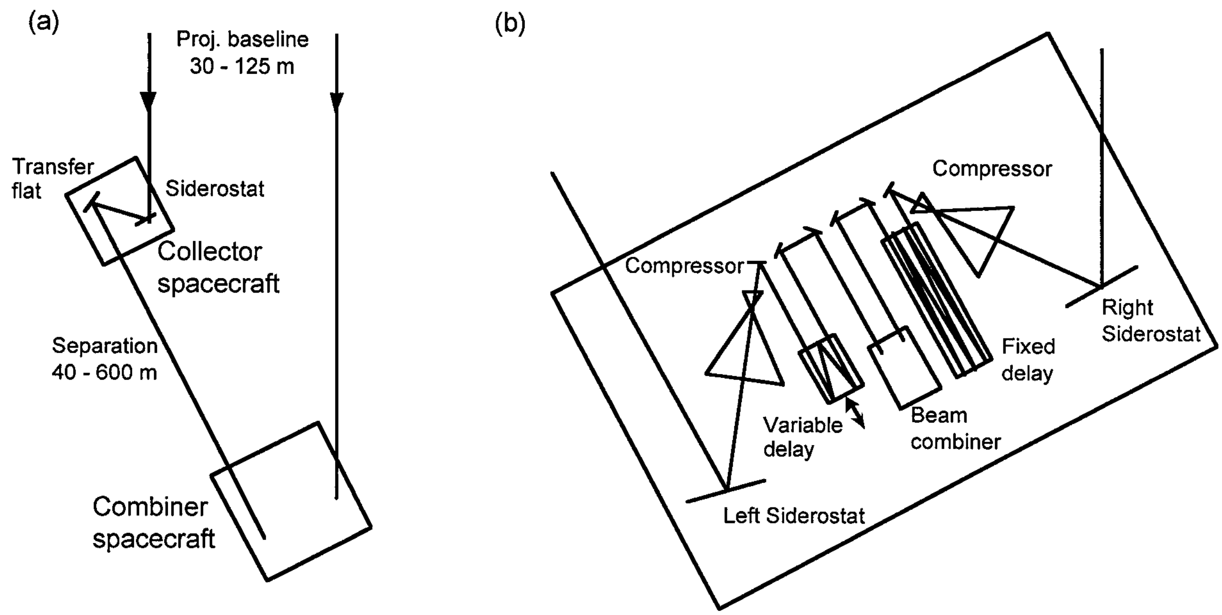


Figure 1. (a) Schematic formation configuration. (b) Combiner optics schematic.

instrument. The right gauge is a standard heterodyne metrology gauge. The left gauge monitors both the path internal to the combiner (from the beam combiner out to the left combiner siderostat) and the external path (from the left combiner siderostat to the collector siderostat). A novel phase modulation scheme allows us to separate the signal returns from two retro-reflectors, one located near the left combiner siderostat, the other on the on the collector siderostat (Fig. 1b).

The principle of operation is as follows. In a standard heterodyne metrology gauge, the *target* beam that propagates along the path to be measured, is given a frequency shift $f_{\rm het}$ with respect to the *local* beam. The two beams interfere at the photodetector producing a sinusoidal voltage output whose phase changes by 2π radians when the optical path length is changed by one optical wavelength (Fig. 2a). The phase of this *unknown* sinusoid is measured against a *reference* sinusoid. If phase modulation at frequency $f_{\rm pm}$ ($>f_{\rm het}$) is now added to the target beam, the photodetector output resembles Fig. 2b.

The original heterodyne waveform can be recovered by mixing (b) with a sinusoid at $f_{\rm pm}$ (c) and removing the high frequency mixing products. This process is *demodulation*. The amplitude of the resulting waveform depends on the phase relationship between (b) and (c): if they are in phase, the demodulated output has maximum amplitude (Fig. 2d); if they are in phase quadrature, the demodulated output is zero (Fig. 2e).

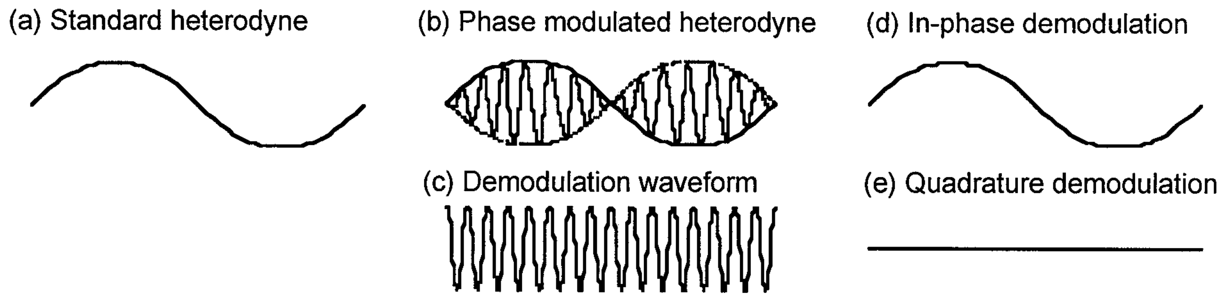


Figure 2. Modulation scheme for dual target metrology.

These properties can be used to isolate the returns from two retroreflectors (A and B) offset in range by Δx along the same path. The B retroreflector assembly is partially transmitting. Choosing a phase modulation frequency $f_{pm} = c / (8\Delta x)$ ensures that the photodetector output waveforms from A and B are out of phase by 90 degrees. This output is split equally into two channels, 1 and 2. The phase of the demodulation waveform for channel 1 is chosen to be in phase quadrature with the return from B; the B return is nulled out, leaving the demodulated waveform from A. Similarly, the channel 2 output is the demodulated signal from B. The phases of these two waveforms are then measured separately against a reference waveform, as in the case of standard heterodyne metrology.

This system, shown in Fig. 3, has been successfully tested in the lab, and an isolation of 60 dB has been demonstrated between the two channels, i.e. the demodulated voltage amplitude from a single retro-reflector can be suppressed by a factor of 1000. The phase modulation frequency is 62.5 kHz for a spacecraft separation of 600 m, rising to 940 MHz for the shortest configuration with 40 m separation. This is sufficient to meet the 10 nm performance requirement for the StarLight mission. The dual target metrology is described in more detail in reference [2]. The technique also suppresses the self-interference error due to polarization leakage [3].

We are currently working on developing components and integration techniques that will allow us to implement a space qualified version of the system.

2.2 Metrology System Components

The laser for the StarLight metrology system needs to satisfy both rigorous functional and environmental requirements. In particular, the wavelength is required to be greater than 1.1 μm so that metrology light does not contaminate the visible starlight signal. The laser must provide high optical power (> 200 mW) and its frequency characteristics must be such that optical frequency noise can be kept below 100 Hz/root(Hz) between 10 and 1000 Hz. If the laser is not

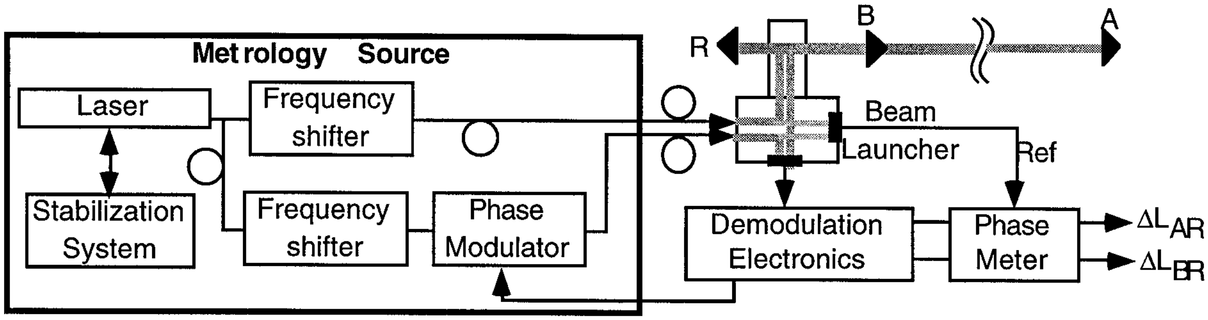
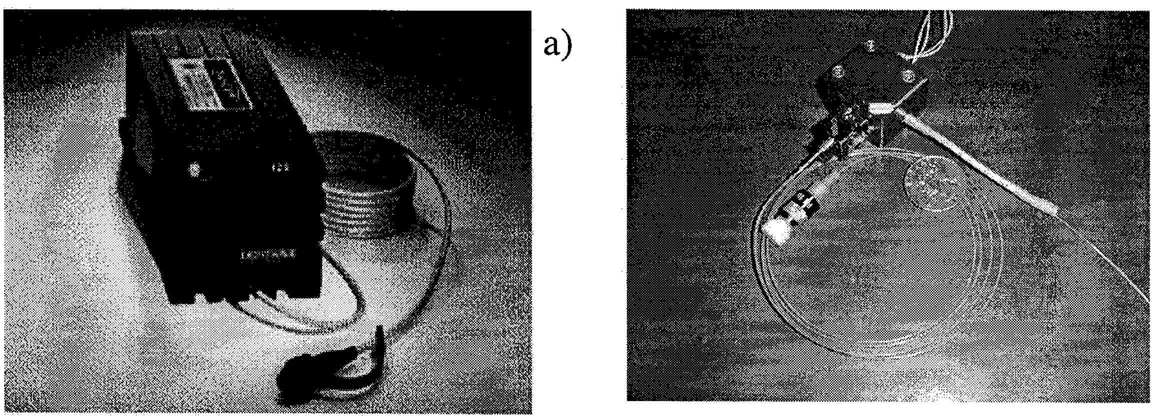


Figure 3. Implementation of the dual target metrology system

quiet enough on its own, this can be obtained by locking the laser to an external cavity, i.e. the laser must be tunable.

We chose a Nd:YAG Non-Planar Ring Oscillator (NPRO) laser operating at 1.32 um wavelength as the baseline laser for the metrology system. The testbed demonstrations have been implemented with commercial lasers from Lightwave Electronics Corp. The flight version of the system requires much greater reliability and lifetime. We have therefore, with support from Lightwave Electronics, developed a completely re-designed version of the NPRO laser, with laser welding of all critical-alignment components and a drastic reduction of the internal optical paths. The commercial and JPL packages are shown in Figure 4. The pump light is delivered to the Nd:YAG crystal via a multimode fiber through a specially designed ferrule that



a) b)

Figure 4: Metrology laser: a) commercial NPRO laser, and b) JPL redesigned externally pumped package.

accomodates up to three pump diodes. The ability to pump a single crystal with three diodes greatly enhances the reliability and lifetime of the laser.

Currently our free-running lasers do not meet the frequency stability requirements of the mission, and an external frequency stabilization system is used. Because we need only a modest improvement in the frequency stability, we plan to use a simple transmit/reflect architecture in which the laser frequency is locked to the side of the cavity resonance peak.

All components in Fig. 3 inside the Metrology Source are interconnected using polarization maintaining fibers. Each component is pigtailed with input and output fibers that are fusion spliced together. Fusion splices have negligible loss and polarization degradation. Fiberoptic interconnects greatly simplify the testing and integration process by completely removing any need for inter-component alignment, significantly simplify the space-qualification process, and save weight and size compared to a stable optical bench and mounts. Even for laboratory use, fiberoptic integration leads to much lower integration costs, especially in terms of time, pain and suffering, although the cost for individual components may be higher.

3 ANGULAR METROLOGY

The purpose of the angular metrology is to provide a sensor to ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics. The sensor is an Intensity Gradient Detector (IGD) shown in Fig. 5. It consists of four photodiodes mounted at the center of the Collector transfer flat (Fig. 1b), with a separation of 2 cm. The linear metrology laser light incident on the IGD from the Combiner has a Gaussian beam shape and nominally illuminates the photodiodes as shown in Fig. 5. When the metrology beam is centered on the IGD array, all the detectors see equal intensity and produce identical output signals. If the beam pointing changes on the Combiner it will be observed as a beam shear at the Collector, and the outputs of the IGD detectors will no longer be balanced. By differencing the detector outputs pair-wise and normalizing by the pair-wise sum we can determine the direction and magnitude of the beam displacement from the Collector optical axis. Knowledge of the inter-spacecraft distance enables us to convert this displacement into a pointing error signal for the combiner siderostat. Figure 6 shows the estimated angular resolution that can be obtained with this sensor, engineered to be limited by photon shot noise and electronics noise.

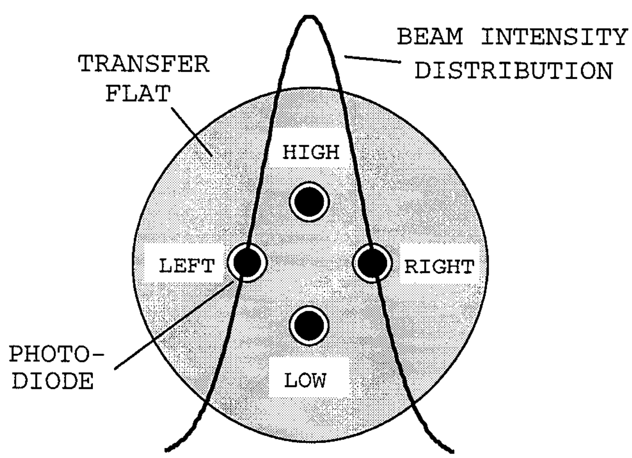


Figure 5. IGD photodiode pattern and beam intensity distribution with respect to the Transfer Flat.

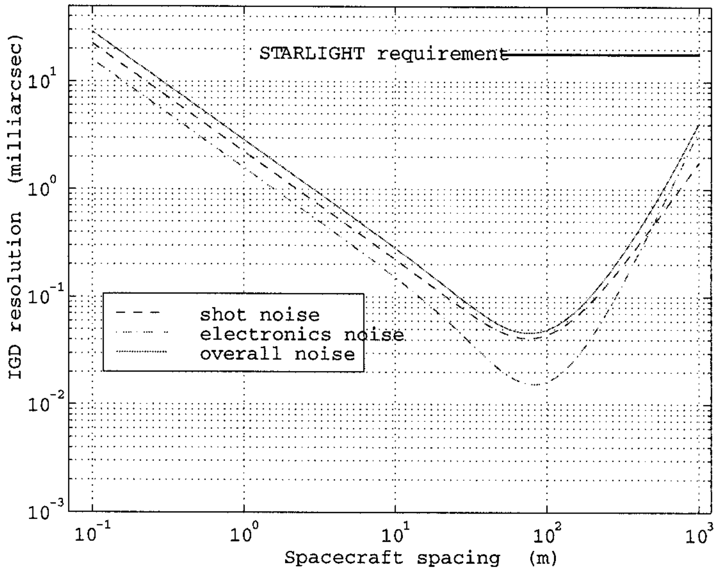


Figure 6. Estimate of sensor resolution, limited by electronics and shot noise.

4 CONCLUSIONS

We have implemented and demonstrated on the ground a metrology system for NASA's *StarLight* mission, a first space-based separated-spacecraft stellar interferometer. The system consists of a novel dual-target linear system and angular metrology for maintaining the pointing. The components and integration techniques needed to implement the system in space are currently being developed.

REFERENCES

[1] O. P. Lay, G. H. Blackwood, S. Dubovitsky, P. W. Gorham and R. P. Linfield, "Design of the ST 3 Formation Flying Interferometer", in "Optical and IR Interferometry from Ground and Space", eds. S.Unwin and R. Stachnik, ASP Conf. Ser. 194, 366, Dana Point, CA, 1999

[2] O. Lay and S. Dubovitsky, "Dual target metrology", NASA Tech Briefs, vol. 25, no. 5, pp. 12a-14a, NPO-21032, May 2001.

[3] S. Dubovitsky, "Heterodyne Interferometer with Phase-Modulated Carrier", NASA Tech Briefs, NPO-20740, February, 2001